Acceleration Independent Along-Track Velocity Estimation of Moving Targets

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Abstract

In the paper a method for along-track velocity estimation of moving targets is presented. This method exploits the along-track interferometric (ATI) phase ramp of a range compressed moving target signal between two or more receiving channels. The slope of this phase ramp is mainly influenced by the along-track velocity but not by accelerations. Hence, acceleration independent along-track velocity estimation is feasible. A verification of the proposed method is performed by using both simulations and real two- and four-channel X-band data acquired with DLR's E-SAR and F-SAR system.

1 Introduction

Most of common parameter estimation techniques exploit the Doppler slope and shift of moving target signals for estimating the motion and position parameters. The Doppler shift is mainly influenced by the across-track velocity whereas the Doppler slope is influenced by two totally different motion parameters; the along-track velocity and the across-track acceleration. Thus, it is impossible to separate both parameters using e.g. a matched filter bank without having additional knowledge. In [1] acceleration measurement results were presented which indicate that in real traffic scenarios the standard deviation of accelerations of common passenger cars is in the order of 0.5 m/s². Such small across-track accelerations indeed may cause severe errors in the order of tens of km/h in the estimated along-track velocity if these accelerations are neglected. For traffic monitoring applications such large errors are not tolerable and therefore accelerations have to be considered and compensated during the velocity estimation stages. In [2] a technique was presented allowing for detecting accelerations and compensating their influence on the imaging process, but not on the velocity estimation procedure. A velocity estimation method taking into account the acceleration is shown in [3]. By estimating the effective synthetic aperture length or Doppler bandwidth of the moving target signal, respectively, the across-track acceleration and the along-track velocity can be separated. However, this method will only work for strong point like targets with aspect angle independent radar cross section (RCS).

Our proposed method exploits the ATI phase history of range-compressed data between two or more receiving (RX) channels which are not co-registered. The slope of this unregistered ATI phase history is mainly influenced by the along-track velocity, but not by accelerations.

2 Algorithm

For the following derivation we assume that the target moves on ground plane (z = 0) with constant acceleration during the observation time (cf. Fig. 1). The motion equations are:

$$x(t)=x_0+v_{x0}\,t+\frac{1}{2}a_x\,t^2,\quad y(t)=y_0+v_{y0}\,t+\frac{1}{2}a_y\,t^2,\quad (1)$$

where a_x and a_y are the constant acceleration components in along-track and across-track direction and v_{x0} and v_{y0} are the velocity components at t = 0. The along-track position of the target at t = 0 is denoted as x_0 and the across-track position as y_0.

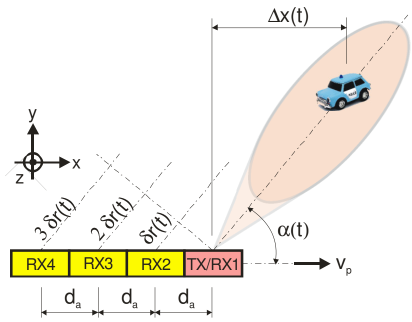

Figure 1 Multi-channel SAR geometry.

The distance from the fore antenna to the target is

$$r_1(t)=\sqrt{\Delta x(t)^2+y(t)^2+h^2}\,,\qquad (2)$$

where h is the altitude of the platform above ground and $\Delta x(t)$ = $x(t)$-$v_p t$ is the along-track difference between the platform and the target and v_p is the platform velocity. At t = 0 the platform is located at x = 0,

$y = 0$ and $z = h$ and so the range from the fore antenna to the target is given as:

$$r_{10} = \sqrt{{x_0}^2 + {y_0}^2 + h^2}\,. \quad (3)$$

Following the derivation in [4] the range $r_2(t)$ from the second antenna to the target can also be written as:

$$r_2(t) = r_1(t) + \delta r(t)\,, \quad (4)$$

where for small along-track antenna separations $d_a << r_1$ the range difference can be approximated by :

$$\delta r(t) = d_a \cos\alpha(t) = d_a \frac{\Delta x(t)}{r_1(t)}\,, \quad (5)$$

whereby cos α is the directional cosine (cf. Fig. 1). The first order Taylor expansion of the along-track interferometric phase history between the channels RX1 and RX2 is then given as:

$$\begin{aligned}\varphi(t) \cong \frac{2\pi}{\lambda} d_a \Bigg\{ & \frac{x_0}{r_{10}} + \frac{v_{x0} - v_p}{r_{10}} t \\ & - \frac{x_0}{r_{10}^3}\left[x_0 \left(v_{x0} - v_p\right) + y_0 v_{y0} \right] t \Bigg\}\end{aligned}\,, \quad (6)$$

where the term in the second line is negligible small in contrast to the other terms. Thus far, Equ. (6) only has been used by the GMTI community for estimating the zero-crossing of the phase history and hence, the broadside position of the moving target [5]. However, also an estimation of the along-track velocity is feasible by exploiting the phase slope:

$$k_\varphi = \frac{2\pi\left(v_{x0} - v_p\right)}{\lambda r_{10}} d_a\,. \quad (7)$$

The along-track velocity is then obtained by:

$$v_{x0} = v_p + \frac{\lambda r_{10}}{2\pi d_a} k_\varphi \quad (8)$$

Note, r_{10} is the distance between the fore antenna and the target at $t = 0$ and not the range r_{img}, where the target is imaged in a commonly processed SAR image or where the signal energy is concentrated in a range compressed image, respectively, if range-cell-migration-correction adapted for stationary targets has been already performed. Hence, r_{10} itself has to be estimated taking the range displacement Δr, which is a function of the across-track velocity v_{y0} or the line-of-sight velocity v_{r0}, respectively, into account. For $x_0 << r_{10}$ the range displacement, which is always negative, can be expressed as:

$$\Delta r \cong \frac{\sin^2\theta_i}{\lambda k_a} v_{y0}^2 = \frac{1}{\lambda k_a} v_{r0}^2\,, \quad (9)$$

where θ_i is the incidence angle and k_a is the Doppler slope of the moving target signal which can be estimated by using e.g. a matched filter bank or fractional Fourier transform. For estimating v_{r0} common ATI techniques which are not range-sensitive may be used. The range r_{10} can then be computed as $r_{10} = r_{img}$-Δr. Apart from the along-track velocity estimation also the across-track acceleration can be estimated by using the Doppler slope estimate k_a:

$$a_y = -\frac{1}{y_{10}}\left[\frac{\lambda r_{10}}{2} k_a + \left(v_{x0} - v_p\right)^2 + v_{y0}^2\left(1 - \sin^2\theta_i\right)\right], \quad (10)$$

where $y_{10} = r_{10} \sin\theta_i$ is the ground range distance to the target and θ_i = acos (h/r_{10}) is the incidence angle.

3 ATI Phase Slope Estimation

3.1 Estimation Accuracy

The accuracy of the ATI phase slope estimation is influenced by noise and clutter, whereas the best reachable accuracy is limited by the signal-to-noise ratio (SNR). To get an estimate of this lower bound, several Monte-Carlo simulations have been performed. In Fig. 3 the standard deviation of the estimated phase slope as a function of SNR and observation time is shown.

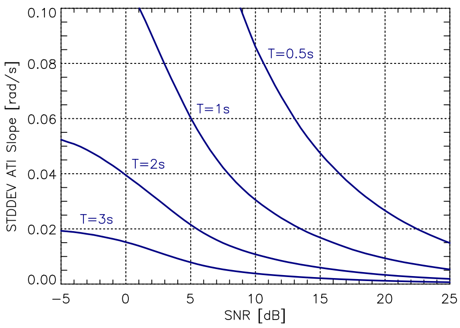

Figure 3 Standard deviation of the estimated ATI slope as a function of SNR and observation time.

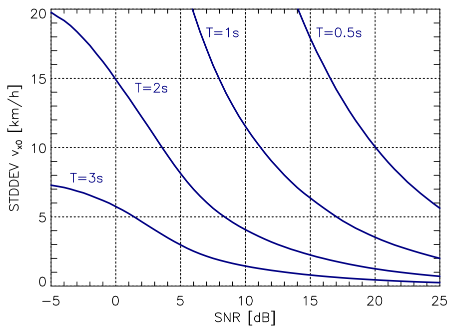

Figure 4 Standard deviation of the estimated along-track velocity for a certain airborne geometry.

Fig. 4 shows the estimation accuracy of the along-track velocity for a certain airborne geometry with parameters v_p = 90 m/s, λ = 3.1 cm, d_a = 0.2 m and r_{10} = 4242 m. Again only the SNR was considered as error source. For a short observation time of 2 s the standard deviation of the along-track velocity is below 4 km/h for target signals with SNR values larger than 10 dB. An increased observation time of 3 s only requires a SNR of 3 dB to get the same accuracy as before.

3.2 Dual-Channel SAR

Before the phase slope can be estimated, the range compressed target signal has to be detected and extracted from the data and clutter suppression has to be performed. One way for suppressing the clutter at dual-channel SAR systems is the application of the fractional Fourier transform and filtering in the fractional Fourier domain. For our approach the same technique as explained in [5] can be used but now with the objective to estimate the slope of the phase ramp. Slope estimation can simply be performed by applying a least-squares fit of a straight line to the ATI phase history. To decrease the influence of phase noise prior to line fitting a threshold operation is performed so that only the phase values from strong signal parts with higher SCNR are used.

3.3 Multi-Channel SAR

In the multi-channel case more degrees of freedom exist and e.g. DPCA can be used for clutter suppression between individual channels (cf. Fig. 5).

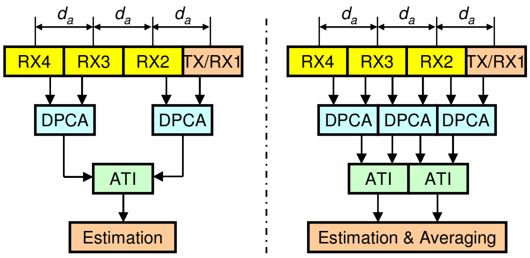

Figure 5 Examples for combining channels.

Co-registration is necessary before DPCA can be performed successfully. For the example shown on the left in Fig. 5 RX2 has to be co-registered with RX1 and RX4 with RX3. The ATI phase history is then computed using both unregistered DPCA signals. For the example shown on the right in Fig. 5 the resulting ATI phase slope between two neighbouring "DPCA channels" is the same as expressed with Equ. (7). Apart from the examples shown in Fig. 5 there are several other possibilities for combining the channels so that more than only one baseline exist. The along-track velocity estimates obtained from several baselines and channel combinations can be combined for increasing the accuracy e.g. by simply taking the average of the different estimates (cf. Fig. 5, right).

4 Experimental Data

4.1 Dual-Channel Data

During the last years several GMTI campaigns were conducted with DLRs E-SAR system using a switched aperture two-channel mode in X-band. In Fig. 6 on the left side a common SAR image containing four controlled ground moving targets is shown. The targets have only moved in along-track direction (antiparallel to the flight path). In that case across-track accelerations are zero and the results obtained from a matched-filter bank with neglected accelerations should be the same as the results obtained with the proposed approach.

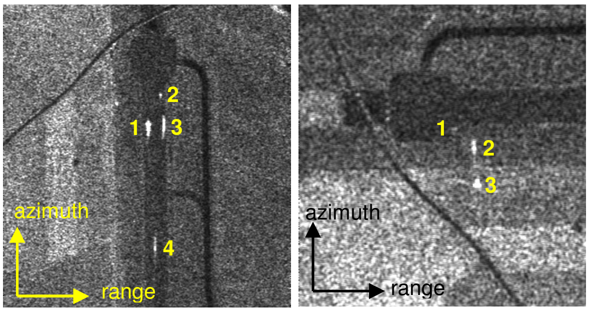

Figure 6 SAR images containing moving targets.

The along-track velocities of these controlled targets measured with DGPS are: 10 km/h, 5 km/h, 9 km/h and 37 km/h. The estimation of the along-track velocities, respectively, with a matched filter bank results in: -9.9 km/h, -3.9 km/h, -8.6 km/h and -35.4 km/h. After extracting the corresponding range compressed signals from the image pairs and bandpass filtering in the fractional Fourier domain, the estimated phase slopes are -2.99 rad/s, -2.91 rad/s, -2.97 rad/s and -3.32 rad/s and the computed along-track velocities are -10.7 km/h, -2.9 km/h, -9.5 km/h and -37.2 km/h. The velocity estimates are in good agreement with the DGPS velocities (max. error of 2.1 km/h) and the estimates obtained from the matched filter bank, as expected. In Fig. 7 ATI phase slope estimation examples for target 1 and 2 are shown.

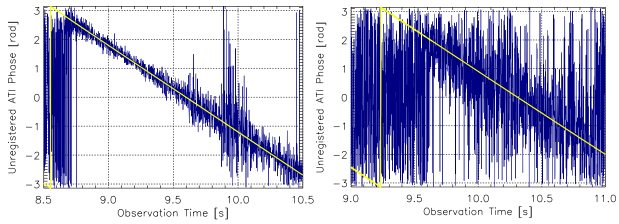

Figure 7 Unregistered ATI phase histories of target 1 (left) and 2 (right) shown at left side of Fig. 6. Blue: without clutter suppression, yellow: clutter suppressed using filtering in fractional Fourier domain.

The SAR image shown on the right in Fig. 6 contains three moving targets travelling only in across-track direction and therefore having no along-track velocity component. As indicated by the defocus in azimuth direction, target 2 has accelerated in across-track direction during the observation time (the acceleration estimate is 0.18 m/s²). With the matched filter bank, an along-track velocity of -9.9 km/h was estimated although the true along-track velocity of the target has been zero. So the estimation error in that case is nearly 10 km/h. The estimate of the unregistered ATI phase slope is -3.21 rad/s corresponding to an along-track velocity of only 0.8 km/h. Hence, for the accelerating target, the along-track estimation accuracy using the ATI phase slope is better than the result obtained from the matched filter bank. It has to be noted that all targets during the conducted experiments were equipped with radar reflectors and therefore have had high SCNR values so that they even were visible in the SAR image without clutter suppression.

4.2 Four-Channel Data

For the acquisition of four-channel data DLR's new F-SAR system operated in X-band with four RX channels was used [6]. Similar investigations as in the previous section were made whereby the channels were combined like depicted on the left in Fig. 5. Additionally, before computing the ATI phases filtering of the DPCA signals in the fractional Fourier domain was performed for further decreasing the disturbing influence of clutter and noise. In Fig. 8 and 9 SAR images of Kaufbeuren airfield acquired during a GMTI campaign in 2007 are shown.

Figure 8 SAR image with automatically detected and repositioned moving targets (range from left to right).

Again no along-track motion of the targets shown in Fig 8. was present so that the along-track velocity estimation errors can be computed. For the targets moving with the velocities of 11, 17 and 45 km/h in across-track direction the estimation errors of the along-track velocity using the proposed approach are 4.2 km/h, 5.5 km/h and -1.6 km/h and the corresponding errors of the matched filter bank -0.4 km/h, 1.7 km/h and 13.6 km/h. The larger velocity error of 13.6 km/h corresponds to an acceleration of -0.34 m/s². The SCNR values of the first two targets are 6 and 9 dB and of the third target 14 dB (the SCNR was estimated from the range compressed DPCA data). Hence, due to the larger SNCR value of the third target the phase slope estimation accuracy is better than for the two other targets. Nevertheless, the estimation errors are in good agreement with the expected ones depicted in Fig. 3 and 4. Note that the phase slope observation time for all targets was in the order of 2 s.

The proposed method also was verified in more realistic scenarios were the targets have moved with non-zero across- as well as along-track velocity components as shown in Fig. 9. The ATI phase slope estimation accuracies depending on SCNR and observation time are in the same order as for the previous example and as expected from Fig. 4.

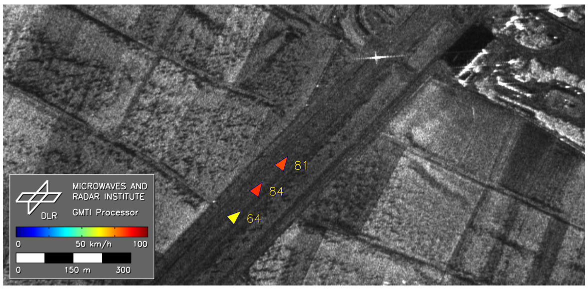

Figure 9 SAR image with controlled targets moving with a heading of 45°.

5 Conclusions

It has been shown that the unregistered ATI phase history in principle not only can be used for estimating the broadside position of a moving target, as already known, but also can be used for estimating the along-track velocity without the negative influence of across-track accelerations. The proposed method was verified using real airborne SAR-GMTI data. At least for airborne applications where the SNR is much higher than at satellite applications, the proposed along-track velocity estimation method seems to be applicable. For the F-SAR data a good performance was observed for SCNR values larger than 10 dB.

References

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